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Thermal Engineering of Mars Entry Carbon/Carbon Non-Ablative Aeroshell - Part 2

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ABSTRACT

Candidate Aeroshell Test models composed of a quasi-isotropic Carbon/Carbon(C/C) front face sheet (F/S), eggcrate core, C/C back F/S, Carbon Aerogel insulation, C/C radiation shield and the C/C close-out were constructed based on the analytical temperature predictions presented in Part One of this work[1]. The analytical results obtained for a simulated Mars entry of a 2.9 meter diameter cone shaped Carbon-Carbon Aeroshell demonstrated the feasibility of the design. These results showed that the maximum temperature the front F/S reached during the decent was 1752 °C with the resulting rear temperature reaching 326 °C in the thermal model.

Part Two of this work documents the thermal modeling and correlation for the Mars Aeroshell test sample and fixture. A finite difference, SINDA/G, thermal math model of the test fixture and sample was generated and correlated to data from an arc jet test conducted at the NASA Ames Research Center's interactive heating facility. A transient thermal analysis was executed for 175 seconds to simulate the heating and part of the cooldown of the sample. Heat transfer coefficients and convective couplings were varied to achieve a good correlation. Results showed that after 45 seconds of heating, the predicted arc jet temperatures versus test data for the front face-sheet were 1396°C versus 1412°C, the predicted temperatures versus test data for the copper coated face-sheet were 1275°C versus 1302°C and the predicted temperatures versus test data for Aerogel core rear surface were 41°C versus 75°C.

INTRODUCTION

A C/C non-ablative aeroshell has many advantages over a standard ablative aeroshell. A C/C aeroshell is non-ablative by nature, and thus would be shape stable during entry. Further, a C/C aeroshell would weigh less than an ablative counterpart, primarily since the ablative layer is eliminated. By utilizing the technology that has been demonstrated under sponsorship from the Mars Exploration Technology Survivability Task, a C/C aeroshell would yield a weight savings over 25% as compared to that of an ablative aeroshell. This lighter weight, shape stable C/C aeroshell structure (having lower possible ballistic coefficients due to the weight savings) would contribute to a more accurate and a more flexible entry profile and make possible a more predictable pinpoint landing.

This technology is well suited for Mars entry and is particularly well suited for landers housing a sample return vehicle, where weight savings are at a premium. This technology also would be usable for high deceleration aerobraking in Mars, Earth, Venus or outer planet atmospheres, where it could be applied for aerocapture or atmospheric entry.

The primary goal of this C/C aeroshell development task was to demonstrate the feasibility and performance of a lightweight C/C non-ablative aeroshell design that integrates advanced C/C materials and structural configurations, low density carbon aerogel for thermal insulation, and thermally stable oxidation resistant and low-emissivity coatings. Also, this task developed thermal modeling design tools for use in designing scaled up aeroshell for flight systems.

In the previous paper, the temperature dependent material properties were generated and transient thermal and structural analysis was conducted using SINDA/G, TRAYS, COSMOSM and Technical Alliance groups thermal model generators and translator software packages. This was for a full scale 2.8 m Mars Entry Non Ablative Aeroshell assembly based on a Pathfinder aeroshell geometry[2]. The aeroshell design composed of a Carbon/Carbon (C/C) face sheets and C/C core structure with a carbon aerogel insulation layer. The front exterior surface were coated with SiC for oxidation resistance and the front surface of the middle plate was coated with copper to provide a radiation shield.

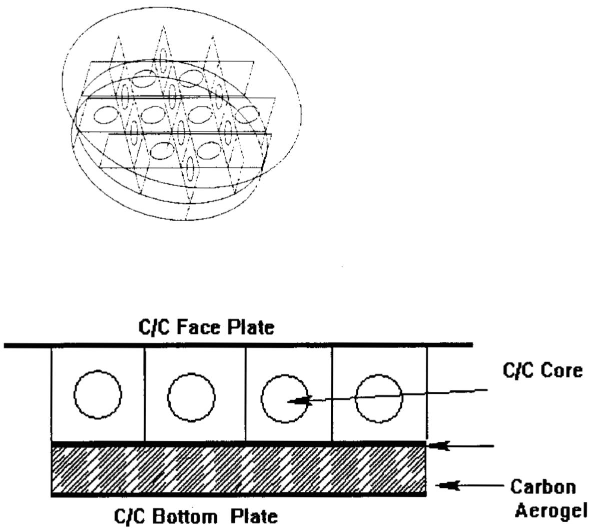


Figure 1: Configuration of Arc Jet Test Models

The carbon aerogel provides significant thermal isolation due to its low thermal conductivity and its minimal radiative transmittance. The thermal properties of carbon aerogel has been investigated by a series of investigators (e.g. ref [3]-[4]). Figure 2 shows the thermal conductivity of carbon aerogel vs. temperature.

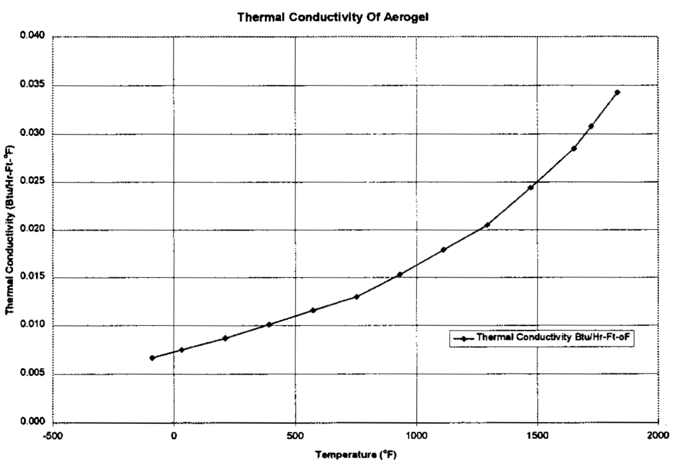


Figure 2 Thermal Conductivity of Carbon Aerogel

The ARC JET TEST

The objective of this arc jet test was to verify the aeroshell structure and its materials can survive a simulated Mars entry and maintain backside heat output low enough for a spacecraft to survive until aeroshell separation. Specially,

1) Verify the thermal performance of the proposed aeroshell models.
2) Verify the aeroshell structure coating and bonding design.
3) Measure temperatures profiles of the front facesheet, internal interfaces and the rear facesheet of the aeroshell structure.
4) Evaluate the thermal elastic response of the aeroshell structure based on the test data.

The arc jet test runs were performed in the Interaction Heating Facility (IHF) of the Arc Jet Complex at Thermophysics Facilities Branch of NASA Ames Research Center, Moffett Field, CA, from March 15 to 22, 1999. The 60-MW Interaction Heating Facility was used to perform 6 runs on 4 C/C non-ablative models. Details regarding test facilities and the models can be found in the reference [2].

Two calibration runs and four Carbon-Carbon Non-ablative test models were aerothermally tested at stagnation heat flux about from 125 to 170 W/cm^2 as measured on a 6" flat-face. The test model was held in place during the test with SIRCA ceramic insulation. Two different test conditions were run, nominally 1500 amps & 20 psia and nominally 1800 amps & 25 psia. The nature of the test is that the arc jet chamber is evacuated and plasma is turned on, then the run test conditions were measured with a 6" FF Copper slug calorimeter / pressure meter to determine the heat flux. Then the test models are inserted into the plasma for 45 seconds, then removed from the arc jet, and the system is shut down, the models are allowed to cool and the pressure is returned to ambient. Surface temperature data were obtained from Infrared pyrometers located inside the test chamber. The test models were instrumented with 7 thermocouples. The assembled test model by itself and integrated into the test holder as shown in Figure 3. The location of the thermocouples are shown in Figure 4. Due to minor variations in the run conditions, the maximum flux varied for each of the four runs. A summary of the test runs is presented in Table 1. It includes the model, conditions, and run time to supplement the reports.

Table 1. Arc Jet Test Run Conditions

	Model 1	Model 2	Model 3	Model 4
Stagnation Pressure (mm HG)	40	48	41	48
Heat Flux (W/cm2)	125	170	130	159
Exposure time (sec)	30	30	30	30
Max Temp (C)	1466	1650	1521	1580

The test procedure can be summarized as

1. Start (Arc jet on).
2. Adjust arc heater parameters (current, mass flow, and model distance from nozzle exit) to the desired test conditions.
3. Swing in the calibration probe for the desired test duration. Data sampling at 20 Hz for calibration.

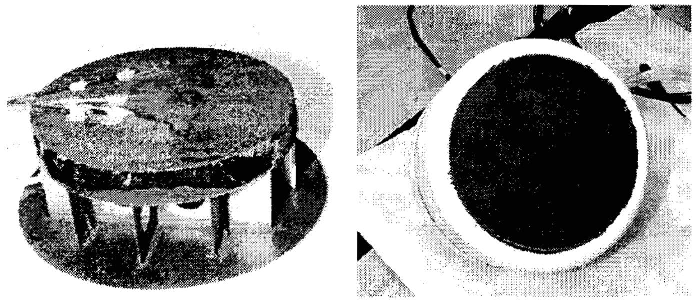
4. If model is run, swing in the test model for the desired test duration. Data sampling

For the test series, the test used test parameters of 100 to 150 W/cm^2 (88 to 132 Btu/ft ^{2} sec) of heat flux, with the **intend to** obtain 1600 ° C (2912 ° F) of surface temperature, which is material dependent. The thermal exposure for this condition is 40 seconds. Additionally, two pyrometers are also used for surface temperature measurement. These instruments are located inside the Test Chamber (M668L) and on West side of the IHF chamber (M190R2) at NASA AMES. Each C/C Non-ablating model is instrumented with 3 Type B T/Cs (back of the C/C facesheet, egg-crate, and the Aerogel side of the first backplate) and 4 Type K T/ Cs (on Aerogel side of the 2nd backplate and back side of the 2nd backplate) for temperature measurement. The calibration probe mounted 6 inch flat-face copper probe has three copper slug calorimeters, one at center, another at 1.01 inch from center, and an outer one at 2.01 inch radius from center, and a pressure tap. All three slugs have 0.31 inch diameter. The center slug has mass of 3.5774 grams; the middle one has mass of 3.5517 grams while the outer radius one has mass of 3.5817 grams. Pressure tap is connected to a 0-15 psia transducers

ARC JET TEST RESULTS

Figure 5 shows the test model in the arc jet plasma flow. All four test models survived the tests with no visible degradation of the front surfaces. The SiC surfaces were discolored, due to reaction of contamination on the surfaces. Erosion of the surface was not measurable. For some of the runs, thermocouples failed to operate during part of the test. All of the test models maintained their thermal structural integrity during the test. When the test models were removed from the arc jet plasma and began cooling, the front face sheets debonded. This is believed to be due to a gas buildup within the core structure which provided a positive internal pressure.

Figure 6 shows the temperature profile results obtained during the test of model 1. The shapes of the thermal profiles were similar in each of the four tests. The Pryrometer temperature represents the front surface temperature of the SiC coated carbon-carbon that is in the plasma flux. TC 1 measures the heat flux passing through the carbon-carbon facesheet. TC 2 measured the heat flux that passes through the core structure, and TC 3 measured the heat flux that passed through the middle facesheet. TC 4 measured the heat flux that passed through the carbon aerogel, and TC 5-7 measured the radial thermal profile on the rear facesheet. As expected, there was a modest thermal lag from the front facesheet to the center facesheet. The most striking feature was the significant thermal lag passing through the carbon aerogel. During the 45 seconds that the arc jet was on for model 1, the front face sheet reached a temperature of 1466 C, but the temperature at the rear face sheet was 75 C. This demonstrates how effective the carbon aerogel insulation is in the design. This characteristic thermal profile and temperature delta was seen in each of the four tests.



Test Model Test Model in Holder

Figure 3: Perspective view of an assembled test model.

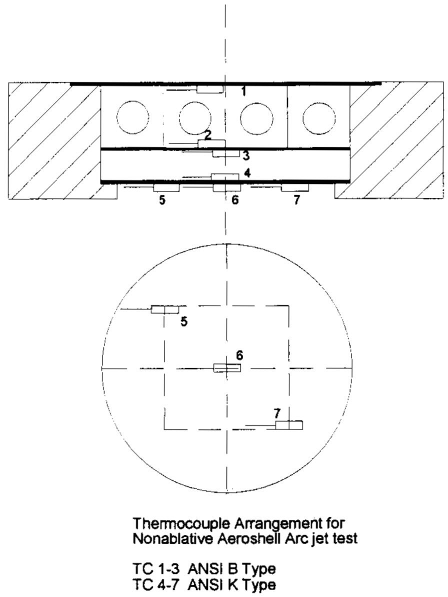


Figure 4. Location of the thermocouple during the arc jet tests and support of the test model in SIRCA insulation

Figure5: Picture of arc jet test

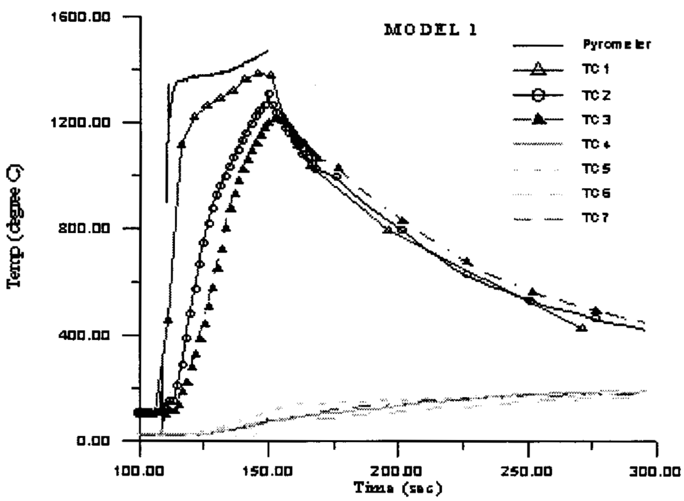


Figure 6: Arc Jet Test results for model 1.

ANALYSIS

To better understand the effects of conduction, convection and radiation that occurred during this test, a detailed thermal model was generated. The thermal model is shown in Figure 7. To account for internal convection while the front face-sheet was in place, a floating air node was used in each core eggcrate and was attached to adjacent external surfaces for convective heating. To account for the radiative effects, surface optical properties of the internal cavity were defined and the geometry was exported into TRASYS and the view factors and conductances were calculation. The surface emissivity of the rear face sheet copper coating, the front face sheet SiC coating and the core were 0.04, 0.8 and 0.8, respectively. Heat was transferred to the Carbon Aerogel core from the rear copper face sheet via conduction. The copper face-sheet is bonded to the aerogel and therefore, the interface conductance between the two materials was not modeled, since the thermal conductivity of aerogel is much lower than that of the epoxy. The rear surface of the Carbon Aerogel core interfaces with the Sirca housing and the ambient air in the test holding fixture rear cavity. Similarly, the interface resistance between the carbon aerogel and Sirca test fixture interface surface was not modeled, since the thermal conductivity of Sirca is much lower than the epoxy. A floating air node was created in the rear cavity connecting the rear surface of the Carbon Aerogel to the holding fixture internal walls and the stainless steel interface bracket. Heat was transferred through the bracket via conduction into the support structure boundary.

Harvard Thermal's TAS was used to create a Finite Element Model. The total number of nodes, plate elements and brick elements used to build the FEA model were 730, 264 and 260,respectively. A total of 7,524 internal radiation conductors were generated to account for the radiation exchange with in the core eggcrate and the face-sheets. A total of 132 external radiative conductors were generated to account for the radiation exchange between the external surfaces and the test tunnel walls. Internal and external convection was accounted for with 485 convective connectors. This Finite Element Model was translated into a Finite Difference, SINDA/G, thermal math model. The resulting SINDA model had 730 nodes and 9470 connectors.

Thermal Analysis:

Thermal Analysis System (TAS) software was used for pre and post processing. The geometry was created in TAS and imported to TRASYS. TRASYS was used to calculate the internal radiation conductors. A thermal conductor and capacitance Gasky Sinda (SINDA/G) network was then generated using TAS. SINDA/G was used for the transient analysis using the "Crank-Nicholson" implicit forward/backward differencing method. See Figure 7 for the thermal modeling/correlation process flow chart. Temperature dependence of thermophysical properties was included in the model. Temperature varying thermal conductivities and specific heat arrays were used for each material type

Analysis Results

Transient results of the SINDA model showed good agreement with the test data, indicating a well correlated model. After 45 seconds of heating, the predicted temperatures versus test data for the front face-sheet, copper coated face-sheet and the Aerogel core rear surface were: 1396°C versus 1412°, 1275°C versus 1302°C, and 41°C versus 75°C, respectively. Hence, the difference between the predicted facesheet to Aerogel core thermal gradient is only 1.3% at the peak temperature. The temperature of the Aerogel core rear surface did not quite correlate with the test data. It is postulated that the thermal coupling between the rear Aerogel core surface and the holding fixture was not well correlated due to the absence of thermal data at that region. For future testing is recommended that, the holding bracket and internal Sirca holding fixture wall temperatures be measured.

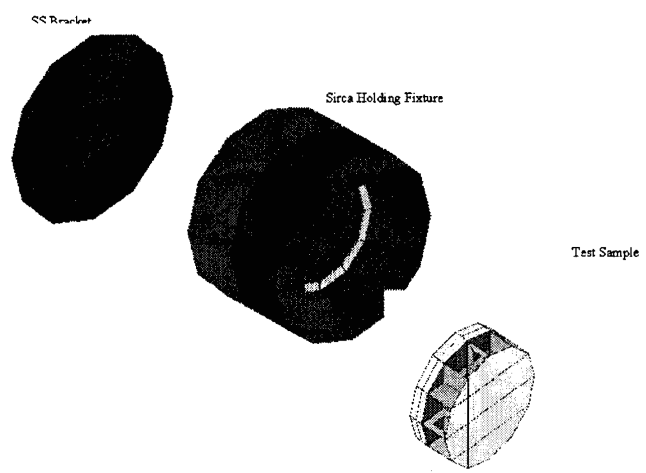


Figure 7: Thermal Model

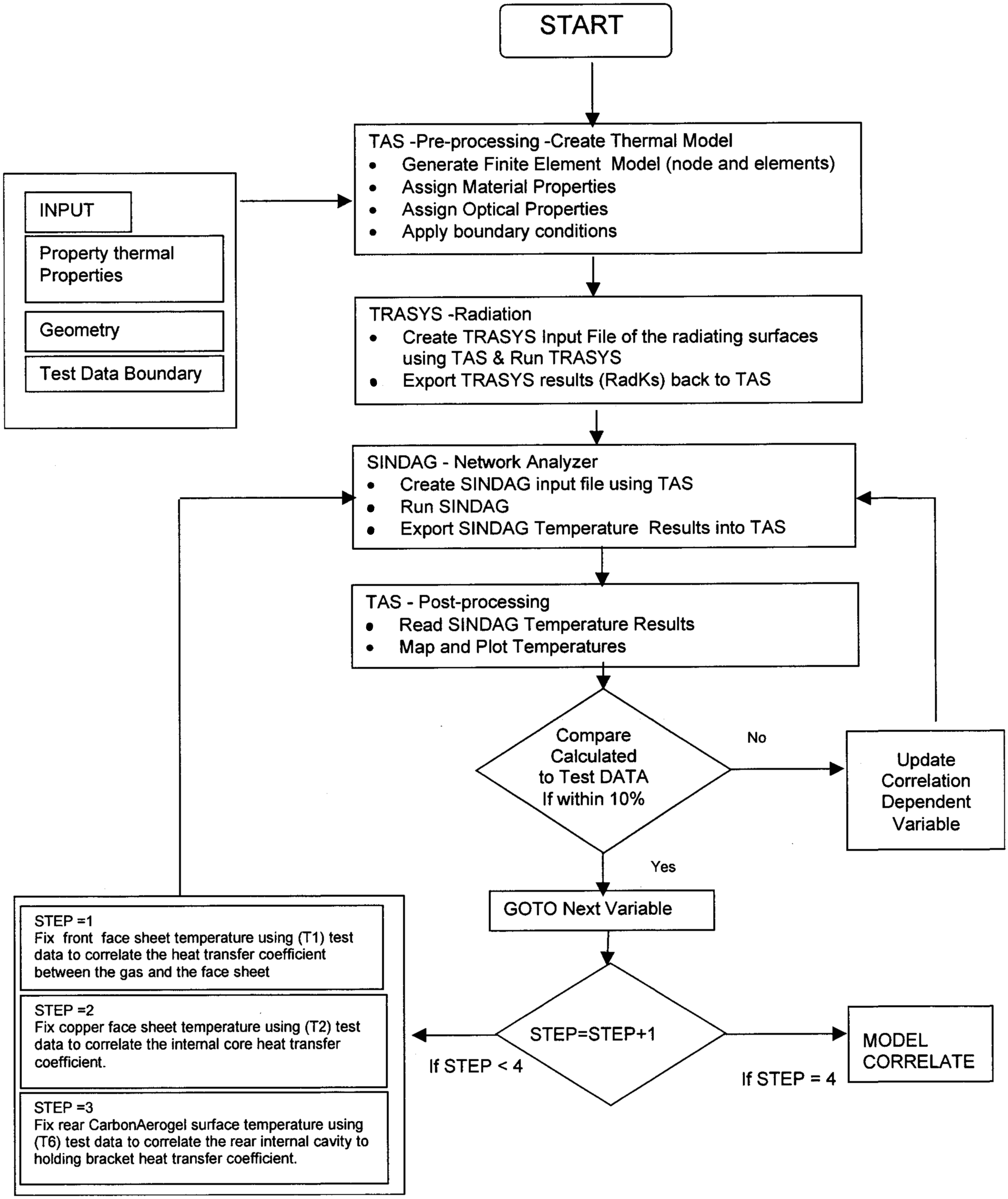


Figure 8: Thermal Modeling Flow diagram

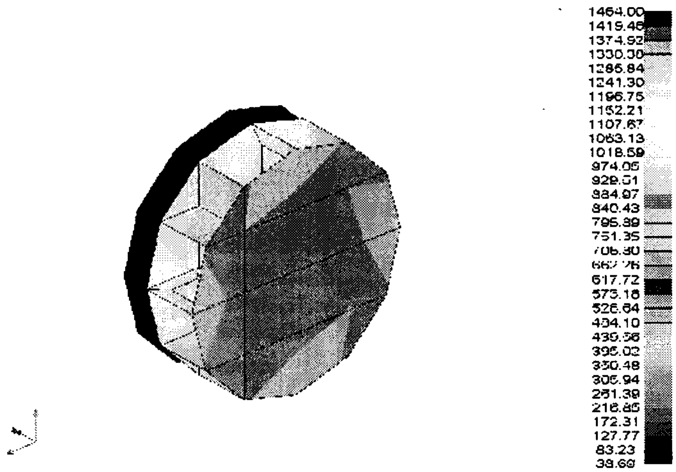


Figure 9. Modeling test results (temperature in degree Celsius)

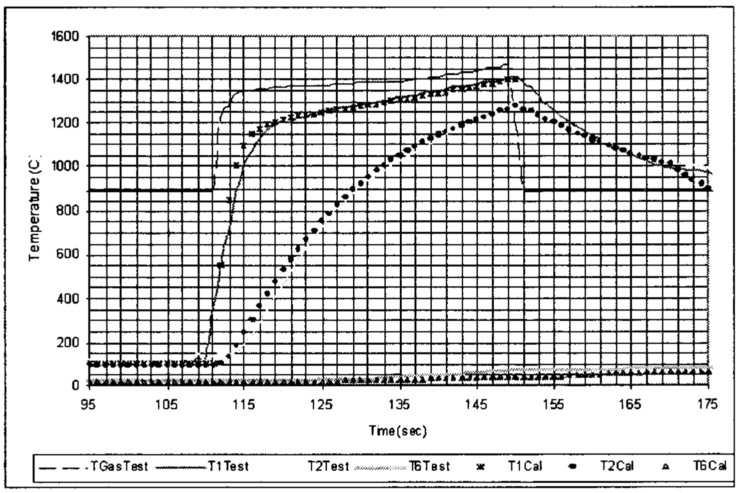


Figure 10: Comparison of modelling to test

CONCLUSION

The test was conducted successfully at the Ames Research Center's Arc Jet Complex. The 60-MW Interaction Heating Facility was used to perform 6 runs on 4 C/C non-ablating models. Two different test conditions were run, 1500 amps & 20 psia and 1800 amps & 25 psia. Test conditions were measured with a 6 inch FF Copper slug calorimeter / pressure probe. The test objectives are met, even though C/C facesheets have debonding problem, by providing test data to verify the design and thermal performance of the Carbon-Carbon Non-ablating Aeroshell model. The validity of the thermal performance of the proposed aeroshell model was proved through the test. The SiC coating on the front face needs to be improved through a more robust process. The measured temperature from the TC's will be used for the thermal/elastic modeling and correlation to perform an optimal design of the face, middle and the back plate of the aeroshell structure

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References

1. B. Wise, P. McElroy, G. Hickey, and S. Lih, "Thermal Engineering of Mars Entry Non-Ablative Aeroshell, Part 1," 29th International Conf. On Enviroment Systems, July 12-15, 1999.
2. Huy Tran et al, "Mars/Pathfinder Back Interface Plate Heat Shield and Designs Verification Tests in the ARC 20 MW Panel Test Facility.," Report for the Mars/Pathfinder Project office of the Jet Propulsion Laboratory, 1995.
3. R.W. Pekala, et.al., "Carbon Aerogels and Xerogels", in Novel Forms of Carbon, D. Cox, J. Pouch, C.I. Renschler, ed: Materials esearch Society Symposium Proceedings (1992).
4. V. Bock, et.al., "Thermal Properties of Carbon Aerogels", J. Non-Cryst. Solids, 185, (1995) p. 233-239.